Arctic Tanker Risk Analysis Project

Task 5.3
Definition and Quantification of External Hazards

prepared for

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March 31, 1992

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8.1 INTRODUCTION

This milestone report is one of a series intended to address all potential hazards affecting the operation of the MV Arctic along the oil transportation route from Bent Horn to Montreal.

The scope of Task 5.3 represented by this report covers external hazards which could contribute to a marine casualty (accident). No judgment is applied at this stage of the work as to whether such a casualty would be likely to result in an oil spill (refer to subsequent analysis in Task 6).

This report focuses on the potential failure rates of specific equipment involved in three categories of navigation systems: Positioning Systems, High Frequency (HF) Communications, and Information Systems (ice and weather). A separate section deals with the issue of icebreaker escort as a form of hazard related to the deliberate operation of two vessels in close proximity. The objective of this report was to define and quantify the variability in the failure rates of specific external hazards along the route defined in Task 2 of the project.

8.2 FAILURE OF EXTERNAL NAVIGATION SYSTEMS

The various external short and long range navigation and communication systems are discussed in terms of their availability and reliability. Availability is defined as the percentage of time that the system is available to the user. Availability is a function of both the effects of the environment and inherent system capabilities (e.g., satellite coverage).

Reliability is directly related to the percent time that a system actually fails through some electronic or mechanical malfunction (regardless of whether the system is actually "available" at the time). Reliability is calculated as one minus the probability of a system failure.

The use or applicability of navigation systems is identified for the various phases of navigation existing between Montreal and Bent Horn (e.g., Harbour, Coastal, etc.). The failure rate of each applicable external navigation system and total system failure hazard is then determined for each route segment. All external navigation systems which are used by the MV Arctic, and those systems which would likely be available to similarly equipped vessels, are discussed (ensuring that this report is applicable to a range of Arctic vessels).

8.2.1 Short Range Aids to Navigation

Table 7 summarizes the availability, reliability, and system failure rates for different navigation, communications, and information advisory systems. Since availability and reliability are separate events, the system failure hazard was determined by the following expression based on standard statistical methods (Guttman and Wilks, 1965):

$$P(A \cup R)=P(A)+P(R)-P(A) \times P(R) \quad [1]$$

where

A is 1 - Availability, and
R is 1 - Reliability.

The following sections describe the approach and methodology used to estimate the values shown.

Table 4. Navigation System Characteristics

Characteristics	Systems							
	Beacons & Racons	LORAN-C	Transit	Omega	GPS	RATT	RAFAX	STAR-2
Availability (Percent)	>98[1]	99.7[1]	99[1]	97[1]	100[1]	75.8[3]	75.8[3]	98.0[4]
Reliability (Percent)	99[2]	99.7[2]	99[2]	97[2]	98[2]	96.8[5]	96.8[5]	99.9[4]
System Failure (percent)	3.0	0.6	2.0	5.0	2.0	27.0	27.0	2.1

Sources:
1 Canadian Coast Guard, Canadian Marine Navigation Statement, 1991

2 United States Departments of Transportation and Defense, 1990

3 Estimated from Canadian Department of Communications Data, 1981-1990 for the Eastern Arctic (based on Resolute); assumed to be near 100% below 65^{o} N.

4 Intera, STAR-2 Performance Data, 1990-1991

5 Canadian Coast Guard Station Iqaluit maintenance records 1986-1991; assumed to be near 100% below 65^{o} N.

8.2.1.1 Daymarks, radar reflectors and buoys

The Federal Review of Tanker Safety (Prevention System Team - Laurentian Region) reviewed an operational analysis of the aids to navigation along the St. Lawrence River and concluded that minimum levels of visual service were met and that aids to radar navigation were also available. This contrasts sharply with the requirements indicated for the Eastern Arctic. Of 45 sites studied in the Eastern Arctic, 25 were assessed as benefiting from the installation of beacons for vessel anchorage and alignment during fueling operations, and six sites required further study (Canadian Coast Guard, 1989).

A study of short range aids to navigation requirements for Bent Horn identified several options which could improve navigation safety. These included daymarks, radar reflectors and RACONs (Ireland, 1989). These options, were designed to assist with alignment while transferring crude oil at Bent Horn terminal. An examination of Hydrographic Chart 7980 for Bent Horn, revealed that no improvements to navigation have been installed at the terminal. This was confirmed by Coast Guard staff (Ireland, personal communication, 1992).

Environment Canada visibility statistics for Bent Horn (1947 to 1988) indicate that a visibility of 2.2 n.m. or greater occurs for 81.1 percent of August and 69.3 percent of September (Ireland, 1989). Therefore, visual positioning by the use of natural marks would have an average availability of 75 percent. Reliability of daymarks is normally dependent on structure, colour, and maintenance, but these constraints do not apply to natural marks.

Because buoys in Arctic waters would be subject to losses from the effects of ice movement and icebreaker operations they are generally non-existent. The Canadian

Hydrographic Service suggests that "Buoys laid in Arctic waters must be regarded merely as temporary and very unreliable aids to navigation" (Fisheries and Oceans, 1982).

8.2.1.2 Radio Beacons

Radio beacons, which are used for direction-finding, are primarily suited to pleasure craft due to the availability of more sophisticated navigation aids for commercial users. They are included here for completeness. "As domestic commercial shipping is no longer required to have RDF [radio direction-finding equipment], this system tends to be a backup navigational aid for those users" (Canadian Coast Guard, Canadian Marine Navigation Statement, 1991).

Radio beacons operate in the LF range of 285 to 400 kHz and coverage is provided for the Atlantic Coast (except Labrador) and the approach to Frobisher Bay (Canadian Coast Guard, Canadian Marine Navigation Statement, 1991). The accuracy of a line of position from a marine beacon ranges from 3 to 10 degrees with coverage out to 200 miles. Availability and reliability are close to 99 percent (source material for all system characteristics are referenced in Table 4). These estimated values are used by the Canadian and United States departments of transportation for radio beacons and RACONs.

8.2.1.3 RACON

Radar beacons, or RACONs are provided to assist with radar navigation in inland waterways, harbours and harbour approaches. RACONs are transponders which are usually fitted to buoys or other structures to enable a positive identification by radar. "The dual band frequency agile RACON is capable of responding to radar interrogation signals either in the X-Band or S-Band, 9320-9500 MHz or 2920-3100 MHz respectively" (Canadian Coast Guard, Canadian Marine Navigation Statement, 1991). RACONs were included in the "Beacons and RACONs" category in Table 4 which indicates an availability of over 98 percent. The Canadian Coast Guard (1991) estimates RACON availability to be 99.9 percent, but suggests that it may be lower in remote locations.

RACONs are positioned along the inland waters, harbours and approaches in eastern Canada, but are not located along the MV Arctic route in the Eastern Arctic. Where available, a radius of coverage of 10 to 40 miles and a positional accuracy of 25 to 75 metres is provided (Canadian Coast Guard, Canadian Marine Navigation Statement, 1991).

8.2.2 Long Range Aids to Navigation

8.2.2.1 Transit Satellite Navigation

The Transit, or Navy Navigation Satellite System which has been in commercial use since 1967, is the primary position fixing method employed on the MV Arctic. It operates on the VHF bands of 150 and 400 mHz and has a 99 percent availability when a satellite is in view (Table 4). The systems reliability is 99 percent with only a .02 percent error rate on control messages which are corrected on subsequent satellite passes (United States Departments of Defense and Transportation, 1990; Stansell, 1978). A position accuracy of 100 metres every 30 minutes at 80 degrees north and every 110 minutes at the equator is possible. Position fixes can be obtained more frequently in higher latitudes because the system is in a polar orbit. The United States Department of Defense intends to continue operation of Transit until the end of 1996 after which time the system will not be operated by or transferred to a civilian agency of the United States Government (United States Departments of Defense and Transportation, 1990). Newer systems such as the Global Positioning System (GPS) will replace Transit.

8.2.2.2 LORAN-C

This low frequency, 100 kHz, radio navigation aid covers the entire Atlantic seaboard from southern Labrador to Florida; no coverage is available in the Arctic. The waters of the St. Lawrence River are covered by the Northeast United States Chain 9960. The Gulf of St. Lawrence is covered by the Canadian East Coast Chain 5930, and the waters extending to the northeast of Newfoundland are covered by the Labrador Sea Chain 7930 (Canadian Coast Guard, Radio Aids to Marine Navigation, 1991). The system's availability is greater than 99 percent and its reliability is 99.7 percent (Table 4).

Fix accuracy using LORAN-C is 460 metres, however, the accuracy of signal propagation and position fixing is reduced by nearness to land, proximity to a baseline extension, distance from a baseline, weather, and ionospheric distortions. Under adverse weather conditions of heavy rain or snow, or near dawn or dusk when ionospheric distortion is greatest, a position error of one mile may be introduced. Large scale LORAN-C charts are corrected for the affects of topography, but errors are most variable within six miles from shore (Canadian Coast Guard, Radio Aids to Marine Navigation, 1991).

"A large portion of the coastal and oceanic traffic carry LORAN-C receivers partially due to the Canadian Navigating Appliances and Equipment Regulations which stipulate that vessels 1600 tons and over operating in Canadian waters must be fitted with a LORAN-C or satellite based position fixing aid" (Canadian Coast Guard, Canadian Marine Navigation Statement, 1991). Even though the United States Department of Defense will discontinue its support of LORAN-C in December, 1994, the United States Federal Aviation Authority and the United States Coast Guard are expanding coverage in the United States; Canada and other nations will be taking over much of the existing system (Canadian Coast Guard, Canadian Marine Navigation Statement, 1991).

8.2.2.3 Omega

This very low frequency 10.2-13.6 kHz navigation system is not employed on MV Arctic and has lost favour to more sophisticated systems. No changes to the system are anticipated until the mid-1990s when the United States Department of Defense will discontinue its support. At present, this system will give a positional accuracy of 3.7 to 7.4 kilometres in eastern Canadian waters, however it is only considered operational to 70^{o} N. Its availability is 97 percent and reliability is 97 percent (Table 4).

8.2.2.4 Decca

The Decca long range navigation system is no longer in use on the East Coast of Canada; the last station was closed in 1986 (Canadian Coast Guard, Canadian Marine Navigation Statement, 1991).

8.2.2.5 Global Positioning System (GPS)

GPS is a satellite navigation system operating in the L Band of UHF at 1227.6 and 1575.42 MHz. As GPS is only recently operational, accuracy estimates are based upon computer simulations. Civilian predictable accuracy is 100 metres. Availability is near

100 percent and reliability is 98 percent (Table 4). GPS is not currently fitted in the MVArctic.

8.2.3 SINSS Shipboard Ice Navigation Support System

Canarctic's Shipboard Ice Navigation Support System provides navigational support through the reception and presentation of ice, weather, and surface information. It is comprised of the View-Fax, Star-Vue and Marine-Vue systems. In addition, ice, weather, and other navigation information is received as radio teletype (RATT) by HF radio equipment. The View-Fax system is used to receive HF radio facsimile (RAFAX) and the Star-Vue system is used to downlink and display microwave imagery from Side Looking Airborne Radar (SLAR) and Synthetic Aperture Radar (SAR). The Marine-Vue system employs a dedicated ice navigation X Band radar. SINSS operation and HF RATT communication is dependant upon the availability and reliability of external communication and information systems.

8.2.3.1 Radio Facsimile and Radio Teletype

Radio teletype (RATT) and facsimile (RAFAX) broadcasts provide various synopses and forecasts considered essential to navigation. These may include ice charts, surface analyses, wave analyses, weather forecasts, isobaric prognoses and other detailed analyses (Canadian Coast Guard, Radio Aids to Marine Navigation, 1991). Ice information is broadcast according to season and availability. Synoptic ship weather data is broadcast according to availability. Extreme weather conditions, such as gale, storm or hurricane force winds, are transmitted immediately (Canadian Coast Guard, Radio Aids to Marine Navigation, 1991). Ice advisory and facsimile broadcasts from Iqaluit and Resolute are conducted at least twice daily and on request during the navigation season. Airborne line-of-sight facsimile transmissions of current ice conditions are provided by ice reconnaissance aircraft on a weekly basis.

The quality of ice charts received by fax transmission is unreliable at times. For example, poor quality charts received concurrently on board the CCGS Henry Larsen and MV Ikaluk during October, 1990 suggested that the quality of ice fax charts was unrelated to the receiving equipment technology (Dickins, 1991). Ice facsimile charts were unavailable for several critical days during the MV Ikaluk voyage mainly due to problems with transmission from Resolute Canadian Coast Guard Radio (Dickins, 1991).

An earlier study also indicated occasions when onboard fax charts were illegible (Wells, 1990).

Resolute and Iqaluit use marine radio equipment such as the Harris HF Model 727 transmitter and Model XH14 receiver. Information is also received via Anik D satellite, but Inmarsat is not used. RAFAX and RATT broadcasts operate in various bands from 122.5 kHz to 20.5 MHz; alternate frequencies are provided should prevailing propagation conditions necessitate a shift to an unaffected frequency. Complete radio coverage is provided; however, the availability of communication systems operating in the LF, MF, and HF bands in the mid and high latitudes is subject to ionospheric disturbances (discussed in detail below).

Two types of ionospheric disturbances resulting from solar flares and sunspot activity are recognized in the literature:

(1) **auroral absorption**, also called polar blackouts, flare blackouts, ionospheric storms, or sudden ionospheric disturbances, and
(2) **polar cap absorption** (Mitra, 1974; Agy, 1979).

Auroral absorption is most pronounced over a limited range of latitude just south of the visual aurora (Agy, 1979). In Canada, this range corresponds to a band between 50 and 65 degrees north latitude. Auroral absorption is precipitated by the incidence of solar flare activity which peaks on an eleven year solar cycle (Mitra, 1974). The duration of interference for varying levels of activity is most probably near 15 minutes before radio attenuation returns to normal (Whalen, 1979). Since the effects of auroral absorption are dependent upon radio wavelength and sometimes propagation is enhanced, "blackouts" can sometimes be overcome by transmitter tuning and frequency optimization procedures.

Polar cap absorption (PCA), which occurs primarily above 65^{o} N and nearly uniformly over the polar cap, is much more of a concern to communications availability because of the range of frequencies affected and the longer duration of interference (Mitra, 1974). "During the 1949-59 sunspot cycle, about forty moderate to strong PCA occurrences took place, each with an average duration of two days. Nearly half of these PCA's occurred in 1957-59, near the peak of the sunspot cycle, but none during the sunspot minimum years 1952 through 1955" (Department of Fisheries and Oceans, 1982). This is confirmed by

Coast Guard Radio Station Resolute where blackouts of one week's duration have been experienced during periods of intense ionospheric disturbances (Lupak, 1992). The daily frequency of occurrence of a major PCA can be said to be 80 days out of 10 years or 0.022 which suggests a LF to HF communications availability of 0.978 for latitudes above 65^{o} N in Canada. However, this value would underestimate the disruptive effects of ionospheric events of less duration.

Canadian ionospheric data are published quarterly by the Department of Communications. These data describe atmospheric characteristics affecting propagation and are used for prediction. Various parameters are measured including the critical frequency, in MHz, of the f_oF_2 layer which is considered an important indicator (Mitra, 1974; Department of Communications, 1992). The critical frequency of this layer indicates the threshold above which HF frequencies are absorbed. For example, a value of 3.3 MHz indicates that frequencies of 3.3 MHz and higher are disrupted. Since the lowest HF fax transmission frequency at Resolute is approximately 3.3 MHz, a f_oF_2 value of 3.3 MHz would indicate a disruption in HF communications availability. The literature does not readily support the specific question of marine HF communications availability at Resolute during August and September; this was determined from Canadian ionospheric data.

A ten year sample (1981-1990) of daily records of ionospheric data for the months of August and September were requested from the Department of Communications. While some months were only available from archives, 17 months of data were readily available for analysis. From the data, the number and duration of ionospheric events were extracted. For this study, an event was defined as the total absorption of frequencies used to transmit HF faxes. In other words, a critical frequency of 3.3 MHz or less.

The Department of Communications uses standards required by the International Scientific Radio Union which define the types of uncertainties associated with each estimated value. Measurements extracted either did not indicate any uncertainty or indicated an intense or high absorption which prevented measurement. Also, values were used which indicated a total blackout qualified by some imprecision in the precise measurement due to the presence of spread echoes.

A total of 1527 absorption events were indicated by ionospheric data from Resolute (Table 5). The longest blackout during the summer navigation season lasted 154 hours in

August, 1989, however, the most frequent event lasted one hour or less. Since 99.5 percent of the events were of less than 16 hours duration, these data were used to illustrate the frequency of ionospheric events, or blackouts in Figure 1.

The availability of HF transmission was calculated as the percentage of time that HF was not absorbed. A total of 12,408 hours were observed during the study period. Since the data is collected hourly, the actual duration of an event of less than an hour is not known, therefore, a most probable period of 15 minutes (Whalen, 1979) was used in the calculation of availability. Table 5 indicates that 3004.5 hours of absorption occurred, from which an availability of .758 was determined (3004/12,408). This value is more representative of the availability of HF communications during a solar cycle than the value of .978 derived from the Fisheries and Oceans estimates of PCA activity because that estimate did not include all ionospheric events, and did not define what the what a 'moderate to strong event' was.

Communications equipment at Resolute and Iqaluit is maintained year -round by Transport Canada. An examination of maintenance records for Iqaluit from 1986 to 1991 was conducted by Transport Canada (Dessureault, 1992). These records provide estimates of reliability for three equipment groups including receiving, transmission and communication control systems (Table 6).

Table 5. Frequency of Ionospheric Events, Resolute, August/September, 1981-1990

Duration in hours	Number of events	Total hours of absorption
1	826	206.5[1]
2	319	638
3	140	420
4	89	356
5	43	215
6	22	132
7	30	210
8	14	112
9	6	54
10	8	80
11	10	110
12	6	72
13	3	39
14	1	14
15	2	30
17	1	17
21	1	21
23	3	69
26	1	26
29	1	29
154	1	154
Total	1527	3004.5

Note 1: It was assumed that an event of less that one hour had a most probable duration of 15 minutes based on Whalen (1979).

Table 6. Communications Equipment Reliability, Iqaluit
Average Failure Rates, 1986-1991

Receiving System	Transmission System	Control Systems
0.006	0.012	0.014

Since the probability of failure of these systems are separate events, communications reliability for Resolute and Iqaluit coverage areas was determined by the following expression based on standard statistical methods (Guttman and Wilks, 1965) :

$$1-P(R \cup T \cup C)=P(R)+P(T)+P(C)-P(R)xP(T)-P(R)xP(C) -P(T)xP(C)+P(R)xP(T)xP(C) \quad [2]$$

where

- **R** is the average failure rate of the receiver system,
- **T** is the average failure rate of the transmission system, and
- **C** is the average failure rate of the communication control system.

Inserting the values provided in Table 6, it can be seen that communications equipment maintained at Iqaluit has a failure rate of 3.2 percent or a reliability of .968 (Table 4). The Iqaluit record is used to represent the overall reliability of Coast Guard radio station communications equipment in Arctic conditions.

8.2.3.2 STAR-2 System

Long range ice reconnaissance is provided by the STAR-2 system synthetic aperture radar on board Intera's Challenger aircraft. Ice information is transmitted directly to the Aydin Vector S Band receiver of the Star-Vue system on the MV Arctic.. The availability of this information is subject to aircraft and STAR-2 system performance. Positional accuracy is dependant on corrections applied on board the MV Arctic to information received from the aircraft.

There are two primary failure modes for the airborne ice reconnaissance system tied to unserviceability of either (1) the aircraft platform or (2) the SAR sensor. Propagation is not considered a problem; unlike HF RAFAX transmissions, the microwave signal (1.5 to

3.9 GHz) used to transmit the SAR image is not affected by ionospheric disturbance (Krakowski, personal communication, 1992).

The following servicabilities were provided by Intera Technologies:

Aircraft availability to commence a mission	98%
SAR fully operational at beginning of a mission	90%*

*SAR availability since August 1991 has been 100%

A failure mode involving only partial loss of SAR capability is compensated by an adjustment to the planned flight path. Consequently, the best indicator of STAR-2 equipment reliability is considered to be the percentage of time when the SAR was totally unserviceable ie. 0% equivalent to 100% reliability.

The Challenger aircraft's Flight Management System integrates positional information received by various navigation systems. The positional accuracy of ice information is dependent on the accuracy of navigation aids on the aircraft. These aids include, Dual Inertial Reference Units (IRU), GPS, LORAN-C, Omega and Dual Distance Measuring Equipment. A single Inertial Reference Unit may result in a drift error of 3.7 kilometres over two hours, therefore, position information provided in the ice imagery must be re-aligned in the Star-Vue system on board the MV Arctic. (Krakowski, 1992).

8.3.0 NAVIGATION SYSTEM APPLICABILITY

Marine navigation is comprised of five phases which closely follow those phases described in the Federal Radio navigation plan (1990). These phases include: Harbour/Harbour Approach, Inland Waterways, Coastal, Oceanic and the additional phase of Arctic Coastal (accounting for the unavailability of LORAN-C). Each phase, defined by the area of operation, determines which navigation systems is generally applicable under different circumstances (Table 7).

Table 7. Navigation System Use

Applications	Systems							
	Beacons & Racons	**LORAN-C**	**Transit**	**OMEGA**	**GPS**	**RATT**	**RAFAX**	**STAR-2**
Harbour	X					X	X	
Inland Waterways	X	X				X	X	
Coastal	X	X	X		X	X	X	X
Arctic Coastal	X		X		X	X	X	X
Ocean			X	X	X	X	X	X

Navigation in harbour and approach areas makes use of beacons, RACONs and radio communications, as well as Vessel Traffic Services in congested waters. Navigation in inland waterways also employs these external navigation systems as well as LORAN-C in more open coastal waters. LORAN-C, Transit, Global Positioning Systems, radio communications, remote-sensing, as well as radio beacons are all used in coastal navigation, but distance from shore limits the use of lights, beacons and RACONs. Navigation in Arctic coastal areas uses coastal systems with the exception of LORAN-C which is unavailable. Ocean navigation uses Omega and all coastal systems except LORAN-C and radio-beacons which are limited by range.

Primary navigation methods employed between Bent Horn and Montreal are more dependent upon visibility and proximity to the shoreline than the availability of navigation systems. Primarily, visual and radar navigation techniques are used in the inland waters of the St. Lawrence River and in the Arctic. Satellite positioning is used throughout the route and is relied upon as a primary aid from the Strait of Belle Isle to Lancaster Sound where the distance from shore limits the use of visual and radar fixing.

LORAN-C is available from Montreal to Fox Harbour, Labrador with only fringe coverage along the Labrador coast.

Short range aids to navigation are well developed along the St. Lawrence River but are relatively non-existent in the Arctic where a mariner must rely on radar and visual navigation techniques to distinguish headlands from land-locked ice floes. Where a ship is station-keeping astern of an ice breaker, greater attention is paid to maintaining relative position on a minute by minute basis. Position fixing on the following vessel in an escort situation is primarily achieved by satellite navigation rather than radar and visual techniques which are used to maintain exact tracks on board the ice breaker. "Escort" in the traditional sense rarely applies to the MV Arctic; these operations are discussed further in Section 5.

There are no external short range navigation aids installed at Bent Horn which could provide sufficient accuracy for maintaining position while transferring oil.

8.4.0 COMBINED FAILURE RATES OF EXTERNAL NAVIGATION SYSTEMS BY ROUTE SEGMENT

The characteristics of availability and reliability (summarized in Table 7) were used to determine the combined potential for navigation system failure for each route segment where specific systems are applicable (Table 5). The approach to combining individual systems failures recognized that a redundancy exists among position information systems, as well as among ice chart information systems.

Table 5 divides Canarctic's route according to some navigation phases used to categorize the system applicability (Table 7). For example, harbour navigation techniques are used in Routes 1 and 11 (Table 7). Navigation systems applicable to Arctic Coastal areas are used from Route 2 through 7. Coastal navigation systems are applicable to Routes 8 and 9, and Route 10 is categorized as an Inland Waterway. The problem then becomes one of combining the failure rates of applicable systems in each route segment to arrive at a profile of external hazards related to navigation/ communications/information systems failures along the entire route.

Table 8. Navigational Phases: Canarctic Route

	Route Segment										
Phase	1	2	3	4	5	6	7	8	9	10	1 1
Harbour	X										X
Inland Waterway										X	
Coastal								X	X		
Arctic Coastal		X	X	X	X	X	X				

An area with a number of alternative external positioning systems will have a lower overall navigation failure rate than an area dependent on a single system. The possibility of total navigation failure requires the simultaneous failure of all available systems along any given route segment; the conditional probability of such an event is calculated as the product of the individual system failure rates.

Similarly, ice charts can be provided by either RAFAX or the airborne STAR-2 system providing a measure of redundancy. The total failure rate of information systems can then be expressed in the same manner as for navigational systems.

Using this approach, the total failure probability is then calculated as:

$$\mathbf{1-P(PS\ U\ C\ U\ IS)=P(PS)+P(C)+P(IS)-P(PS)xP(C)-P(PS)xP(IS)} \quad [\ 3]$$
$$\mathbf{-P(C)xP(IS)+P(PS)xP(C)xP(IS)}$$

where

PS is the failure rate of redundant Positioning Systems,
C is the failure rate of HF communications, and
IS is the failure rate of redundant Information Systems.

Table 9 summarizes the values used to arrive at an estimate of total failure for external navigation systems.

Table 9. Navigation System Failure Rate by Route Segment-Aug/Sept

Route Segment	**Positioning Sys**				**HF Comm**	**Information Sys**		
	Beacons & Racons	**LORAN C**	**Transit**	**GPS**	**RATT**	**RAFAX**	**STAR 2**	**Total Failure**

1	.3	-	-	-	.27	.27	.021	.274
2	-	-	.02	.02	.27	.27	.021	.277
3	-	-	.02	.02	.27	.27	.021	.277
4	-	-	.02	.02	.27	.27	.021	.277
6	-	-	.02	.02	.27	.27	.021	.277
7	-	-	.02	.02	.27	.27	.021	.277
8	.03	.006	.02	.02	0.0	0.0	-	<.001
9	.03	.006	.02	.02	0.0	0.0	-	<.001
10	.03	.006	-	.02	0.0	0.0	-	<.001
11	.03	-	-	-	0.0	0.0	-	.03

Note 1: Non-applicable for Route Segment 1 since no alignment systems exist at Bent Horn
Note 2: Total failure for each Route Segment is equal to the product of positioning system failure rates plus the RATT failure rate plus the product of RAFAX and STAR-2 failure rates (refer to equation [3])
Note 3: Non-applicable systems are indicated by a dash

The results show that the total external navigation equipment failure probability ranges from less than .001 along Route Segments 8, 9 and 10 to .277 along Route Segment 1. The seven most northerly segments are much riskier in terms of the potential for navigation failures, than the southerly areas (reflecting the lack of redundancy of external aids, propensity for HF interruptions, and importance of ice information in Arctic navigation).

The failure rates determined in this study for the navigational season of August and September are generally applicable on an annual basis (the only temporal data used in the analysis was HF propagation).

8.5.0 Hazards During Icebreaker Escort

The MV Arctic is required to have a Canadian Coast Guard icebreaker escort while transiting from Bent Horn to Resolute, N.W.T. Although hazards associated with icebreaker escort were not identified in the Zurich Hazard analysis, casualties resulting from such operations are considered most applicable to the category of external hazards at this stage in the study.

The probability of the MV Arctic experiencing a casualty, given that it is in an escort situation, can be treated as the probability of causes (such as ice, low visibility, human error, and equipment failure) resulting in an effect such as a collision. The analysis of casualties associated with escort operations is treated separately from other navigation related external hazards discussed in Sections 2 and 3.

Icebreaker escort is defined as an operating configuration in which certain casualty types may be more likely because two vessels are operating in unusually close proximity to each other.

Transport Canada has contracted a review of all operational data regarding escorts in order to provide a rational method for assessing vessels under escort under the new Ice Regime Shipping Control System (Norlands Science & Engineering, 1992 - work in progress). A database of commercial and Transport Canada escorts in the Arctic and East Coast waters has been compiled. Escort distances, ice conditions, visibility, vessel speeds, types of damage, and other conditions and events have been entered into the database. Analysis of the database will provide information on the number of collisions per mile from a variety of causes (i.e., collisions during escort situations with poor visibility). These results will be used to provide further input into Task 6 when the database becomes available in mid-April.

8.5.1 Possible Casualties During Traditional Escort Operations

Historically, three types of casualties have occurred during escorts.

1. The following ship may collide with the stern of the escort vessel. This occurs when the escort vessel encounters an ice obstacle, stopping or slowing the escort substantially. As vessels normally follow within 1/2 mile or less of the escort in order to take advantage of the clear track through the ice, very little distance is available for stopping. In an emergency the following vessel may be able to slow down by driving out of the track and into the ice. Normally, the escort warns the following vessel of any possible slow downs; however, the ice obstacle may not be noticed in time. Contributing causes include ice, human error (not noticing the ice), poor visibility, darkness, equipment failure (following vessel loses control of steering).

2. The following vessel may be damaged by a piece of ice which has been submerged under the escort vessel and re-surfaced in the path of the following vessel. The cause is related to natural variations in ice conditions and additionally in some cases to human error (not noticing the ice).

3. If a vessel is beset in ice, it may request the icebreaker to come to its aid. As the icebreaker attempts to free the vessel, a possibility of collision exists. If the icebreaker misjudges ice resistance and is moved off position by a piece of ice while manoeuvring close by the vessel, it can strike the vessel. The causes are related to ice and human judgment.

To provide an indication of the frequency of these types of hazards relative to other hazards of arctic shipping, the accident reports from 1975-1989 of the Transportation Safety Board were examined. Of the 298 accidents reported, only two could be attributed to collisions of the following vessel with the escort, three accidents were related to ice in the icebreaker track (not likely to affect a Class IV vessel like the MV Arctic), and one accident was a collision between an icebreaker and a beset vessel.

8.5.2 Possible Casualties Related to MV Arctic Escort Operations

These historic types of collisions can not be directly applied to the escort configuration used by the MV Arctic. The MV Arctic is a unique case in that its icebreaking capability is comparable to that of its escorts, both being Arctic Class IV ships. The icebreaker escorts have the advantage of better maneuverability.

In the majority of MV Arctic escorts, the escort follows behind the MV Arctic and only assists in turns where it can widen the track in the ice for the longer vessel, resulting in a shorter turn. Icebreakers also assist at the Bent Horn terminal where they breakout the ice so that the MV Arctic can easily maneuver out of the terminal area.

The lead position of the MV Arctic also reduces the instances where pieces of ice in the ice track could damage the vessel (unlikely anyhow given the ice-strengthened hull of the MV Arctic).

This leaves three possible situations where damage can occur during escort: 1) collision with the icebreaker escort as it steams beside the MV Arctic during a turn and 2) collision in the case that the MV Arctic is beset and the icebreaker is working to free the vessel and 3) collision at the Bent Horn terminal as the icebreaker breaks ice near the MV Arctic.

Ice conditions where the tanker is assisted in turns vary widely and cannot be defined precisely. Distance available to complete the turn, weather conditions and operational considerations are all additional factors in the decision to use this procedure. Given the icebreaking capabilities of the MV Arctic, presence of multi-year ice (in any concentration) or heavily ridged first year ice would be required in order for this type of escort assistance to be requested.

Ice conditions required to trap the MV Arctic in ice are extreme. Based on the case of November 1983 when the MV Arctic was beset in Lancaster Sound, total concentrations of more than 9 tenths with 3-4 tenths of old ice and heavy ice pressure are necessary to set-up this situation.

Collision involving an escort vessel will be treated in Task 6.0 as a separate event, in the same manner as collision, striking and grounding. Quantification of the factors contributing to collisions during escort will need to incorporate the results of associated analysis dealing with natural hazards and human error.

8.6.0 CONCLUSIONS

External hazards are dominated by the failure of navigation related systems. Taking redundancy into account, the total failure probabilities along Route Segments 8 to 11 are negligible. Failures of navigation systems along the northerly segments are dominated by the high frequency of interruptions of HF communications.

Excluding problems with HF communication and radio facsimile transmission, the failure rate of all other navigation related systems is negligible along the entire route. (Ed. note - The high incidence of RAFAX failure due to propagation problems in the north is an impediment to navigation but the type of ice navigation that is required in the high Arctic, particularly Bent Horn requires a much higher level of information and is thus less of an hazard then might be thought.)

An evaluation of icebreaker escort in the context of the MV Arctic operations concluded that collisions related to escort are most appropriately treated as a distinct casualty category in Task 6. Concerns of traditional escort operations (following ships running into the escort, following ship damaged by ice in the track) do not apply to the MV Arctic. The term "escort" in MV Arctic operations is used to describe short term assistance while maneuvering in heavy ice.

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